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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF AIR-COOLED TURBINE

BLADES IN TURBOJET ENGINE

VII - ROTOR-BLADE FABRICATION PROCEDURES

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SUMMARY

An experimental investigation was conducted to determine the cooling effectiveness of a wide variety of air-cooled turbine-blade configurations. The blades, which were tested in the turbine of a commercial turbojet engine that was modified for this investigation by replacing two of the original blades with air-cooled blades located diametrically opposite each other, are untwisted, have no aerodynamic taper, and have essentially the same external profile. The cooling-passage configuration is different for each blade, however.

The fabrication procedures were varied and often unique. The blades were fabricated using methods most suitable for obtaining a small number of blades for use in the cooling investigations and therefore not all the fabrication procedures would be directly applicable to production processes, although some of the ideas and steps might be useful. Blade shells were obtained by both casting and forming. The cast shells were either welded to the blade base or cast integrally with the base. The formed shells were attached to the base by a brazing and two welding methods. Additional surface area was supplied in the coolant passages by the addition of fins or tubes that were brazed to the shell. A number of blades with special leading- and trailing-edge designs that provided added cooling to these areas were fabricated. The cooling effectiveness and purposes of the various blade configurations are discussed briefly.

INTRODUCTION

Current gas-turbine engines contain large quantities of high-temperature materials in the engine components downstream of the compressor. Means of building gas-turbine engines with reduced critical material content must be determined in order to conserve these materials.

The critical-material content of the gas-turbine engine can be reduced by a materials substitution program. This program includes redesign to eliminate non-essential weight, reduction of the use of high-alloy steels for high-stress - low-temperature application, and the use of protective coatings on low-alloy steels for high-temperature applications where the main problem is oxidation rather than strength. In order to reduce, or to eliminate if possible, the critical metals in turbine blades, some method of cooling the blades may be utilized so that the blade temperatures can be reduced enough that the noncritical alloys will have sufficient strength to withstand the centrifugal, thermal, bending, and vibratory stresses imposed by turbine operation.

For turbojet engines, air cooling appears to be the most practical blade-cooling method devised up to the present time. An investigation has therefore been initiated at the NACA Lewis laboratory to determine the cooling effectiveness of a number of air-cooled blade configurations installed in a modified commercial turbojet engine. The fabrication of these blades required special and varied procedures to obtain blades that could be well cooled and at the same time had sufficient strength to withstand the stresses imposed in gas-turbine operation. The cooling-passage surface area of the blades was increased by the addition of either fins or tubes, which were furnace-brazed to a cast or formed shell, and various means were investigated for film cooling or conduction cooling the leading and trailing edges.

The air-cooled-blade fabrication methods are reported herein. Many of the procedures are applicable to commercial production methods, but some procedures may be slow or costly; however, a study of these procedures will possibly be valuable in bringing forward new ideas for air-cooled-blade production.

COOLED-BLADE DESIGN AND FABRICATION CONSIDERATIONS

There are a number of considerations that affect the fabrication of cooled gas-turbine blades. The choice of an alloy is an important item. Ordinary carbon steels lose strength rapidly at temperatures above 900° F, but there are a number of steels containing at least 95-percent iron that have good strength properties at metal temperatures up to 1100° F. Use of carbon steels for turbine blades therefore does not appear practical because of the great gains in strength properties made by small percentage additions of alloying elements, such as chromium, molybdenum, titanium, boron, and vanadium.

Blade fabrication will be influenced by blade configuration, and conversely, the configuration will be influenced by fabrication limitations. In order to insure adequate cooling, the blades must be of a shape that will permit the flow of sufficient cooling air through a passage containing surface area adequate for the blade to be cooled to the temperature limits imposed by the strength of the blade material. At the same time, any compromises in the aerodynamic efficiency of the design must be minimized or eliminated. Most cooled blades will probably have very little aerodynamic taper because of the desirability of having a uniform cooling passage cross section from root to tip. Twist is possible; however, for some designs it is unnecessary in the rotor blades. Taper in the walls of conventional shell-supported blades is probably required in order to reduce stresses near the blade root.

Fabrication of blades should be by methods adaptable to production to permit high production output at low unit cost. This purpose suggests that the designs should be as simple as possible consistent with good cooling performance. The use of low-alloy steels permits a greater latitude in fabrication procedures and indicates the use of formed, brazed, welded, or brazed-and-welded blades. Increased surface area in the coolant passage will probably be supplied by the use of metal inserts brazed to the blade shell. Low-alloy steels require oxidation and corrosion protection both in storage and during engine operation. This protection may be supplied by means of protective heat-resistant coatings, such as aluminizing, chromizing, and ceramic-type coatings.

Heat-transfer investigations have been conducted on a large variety of air-cooled turbine blades and are reported in references 1 to 6. From the results of the investigations on blades that incorporated increased surface area in the coolant passage of the blade but used no special means of cooling the leading and trailing edges (references 1 to 3), it was found that the midchord portion of the blade cooled very well, but the leading and trailing edges were as high as 500° F above the temperature at the midchord. Efforts were therefore made to determine means of lowering the temperatures in these regions. Rounding the leading edge reduced the leading-edge temperature approximately 75° F (reference 4), but further temperature reductions were thought necessary. A number of special cooling methods at the leading and trailing edges were investigated (references 4 to 6). These special methods included several types of film cooling, conduction cooling by means of copper fins or copper cladding at the leading and trailing edges, and trailing-edge convection cooling where part of the cooling air was discharged through a split trailing edge.

The blade configurations used in the heat-transfer tests were fabricated at the Lewis laboratory. The blades were not necessarily the types that would be suitable for production, but were fabricated to investigate a number of cooling principles.

BLADE-SHELL FABRICATION

Three general types of blade shell were used in this investigation, namely, a shell cast separate from the base, a shell cast integrally with the base, and formed shells. All shells had essentially the same profile as the root section of a J33 turbojet-engine blade and had a constant nontapered, nontwisted internal passage to the tip. This coolant-passage design was used for initial blades because it allowed for ease of tube insertion and better control of brazing technique. Except for the deliberate variations in blade profile at the leading edge, the blade dimensions were maintained uniform within general precision casting and forming tolerances to reduce aerodynamic variations to a minimum. All blades were inspected by use of radiography with particular attention paid to the lower half of the shell and the fillet between the base and the shell. In these locations, shrinkage, tear, and porosity defects would cause excessive cracking when the shell was welded to the base, or if it were integrally cast would cause blade failure during turbine operation.

Precision Cast Blades and Shells

The general methods of precision investment casting (lost wax process) are generally well known but there are no known publications describing the particular application of this process to hollow gas-turbine blades. This type of blade, shown in cross section in figure 1, has thin tapered blade-wall sections and when it is cast integrally with the base, there is a rapid change in cross section at the fillet juncture, which makes sound castings difficult to obtain.

The general steps used for casting hollow blades are shown in figure 2. A wax pattern of the blade is made and the gates and pouring basin are attached, a single coat investment is poured, the blade is cast, and the gates are removed. The details of this procedure are listed in the following paragraphs.

Pattern dies. - Pattern dies for the blade shell (fig. 3) are made of aluminum, brass, or soft metal alloys (bismuth-tin). The aluminum and brass dies are made by machining with correct allowance made for investment expansion, wax shrinkage, and metal shrinkage. This allowance is dependent on the properties of the wax, investment, and casting metal, and since it varies for each application a set of

values cannot be given. Soft metal dies are made by use of a wood
pattern that is finished to the correct size to allow for expansion
and shrinkage of the investment, wax, casting metal, and metal die.
The dies are made by casting either low-melting soft metal over a
wood pattern or by casting over a plaster mold of the wood pattern.
These methods result in good replicas and are highly satisfactory.
Hollow blades require at least a three-part die, as shown in figure 3.
For some blades, the wax pattern for the whole blade can be made in
the same die, but for other blades the wax patterns of the shell and
base must be made separately and are then attached to make the final
pattern. The dies are constructed to allow correct positioning of the
core insert with respect to the blade surfaces and for easy removal of
the metal core from the wax pattern. Die parting lines for the shell
are maintained along the leading and trailing edges.

Wax injection. - High-softening-point, hard, low-shrinkage wax
developed especially for commercial precision-casting work is injected
into the pattern die under pressure. In order to obtain good patterns,
it is important that the wax be at the recommended temperature and
pressure before and during injection. After solidification, the wax
patterns are separated from the die and require careful handling to
prevent distortion.

Mounting and investing. - Wax pouring basin and gates are attached
to the wax blade pattern as shown in figure 2(a) for one method of
gating. This wax pattern is then mounted inside an Inconel flask and
an investment slurry is poured in the flask and vacuumed and vibrated
in order to eliminate gas bubbles and to insure fit between the pattern
and the investment slurry. The flask containing the slurry is shown
in figure 2(b). Burnout of the wax and mold curing are accomplished
by successive slow heatings from room temperature to the desired mold
pouring temperature. Ferrolite investment has been used successfully
for cobalt cast alloy blades but not for steel blades. The curing
time table for Ferrolite is as follows:

Temperature ($^{\circ}$F)	Total heating (hr)
80	24
200 to 900 (25°/hr)	28
900 to 1500 (100°/hr)	6
1500 or above (min.)	12

Ferrolite investment is used without precoat and gives an excel-
lent surface finish; however, it is dense and does not deform
appreciably, thus introducing possible tear immediately adjacent to
the fillet, particularly when casting steel blades. This defect pos-
sibly can be minimized by the use of a more deformable porous-type
investment.

Melting of casting metal. - Alloy melting is accomplished by use of an induction unit (10,000 cycle, 100 kw) and suitable crucibles with enough charge for a single blade. Stock alloys are used for the melts, such as Haynes Stellite 31 (X-40), Haynes Stellite 21, and SAE 4130 and Timken 17-22A[S] steel. For integrally cast steel shells and bases, it has been observed that:

(1) Degassing additions to the melt are necessary; degassing can be accomplished with the addition of 0.2 percent of aluminum. (Residual aluminum less than 0.05 percent.)

(2) Pouring temperatures for SAE 4130 and Timken 17-22A[S] must be in excess of 2900° F and are dependent on gating procedure and mold temperature.

(3) The use of ferroselenium and excessive aluminum apparently increases the tendency for tears to form on integrally cast blades and bases.

(4) Melting and pouring must be performed in a minimum of time.

Centrifugal casting. - As soon as the molten metal reaches the required pouring temperature, which must be determined for each alloy and each mold design, and has been degassified, a crucible containing the melt is placed in the centrifugal casting machine and the mold, which has just been removed from the curing furnace, is placed on top of the crucible and locked in place. The mold is placed so that the chord of the blade lies in the plane of rotation. This arrangement is made primarily to minimize core shift. The mold and the crucible are then rotated as a single unit at an average angular speed of about 175 rpm and at a radius of approximately 20 inches (this condition corresponds to casting force of about 17 times that of gravity) until solidification is complete. After cooling, the cast blades or shells are removed from the molds. Ferrolite investment is removed from the coolant passage by use of electrolytic molten caustic; other investments are removed by hand.

Radiographic inspection. - Three or four radiographs are required for the inspection of each blade. Exposures are made for the inspection of the blade shell, the blade fillet, and the blade base. Rejections are based on the location and type of defect present. Defects of shrinkage, tear, and gas porosity in the lower half of the blade span and in the fillet are cause for complete rejection. The same defects in the upper half of the blade span are cause for rejection only if they are gross. Blade-base defects (generally nonexistant), unless gross, are not cause for rejection.

Formed Metal Shells

Hollow blade shells were produced by fabricating steel tubes with tapered wall thickness of the proper size and then contour pressing and forming them by use of a two-part die and a press. The principal steps in the fabrication of formed blades are shown in figure 4. Details of shell-fabrication procedure are listed in the following paragraphs.

Tubes of correct size for the blade shell can be obtained from seamless tubing or can be formed from sheet stock and butt welded. Sheet stock, which has been used satisfactorily, has been alloy steel, 18-8 stainless steel, Inconel, or copper-clad alloy steel. Many other alloys can undoubtedly be used with equal success. The tapered machined sheets of unclad material are formed to the correct inside contour diameter. These are then heliarc or gas welded along the butt seam. Copper-clad material is formed in the same manner except that the copper is removed adjacent to the area to be welded so that no embrittlement of the weld will occur. Copper need not be removed if Inconel rod is used for welding because a copper-nickel alloy is not detrimental. Tubes, which are obtained from tubing stock, are machine tapered along the outside and fully annealed before pressing and forming.

The tubes with tapered wall thickness are filled with beeswax and positioned on the lower half of the die that is mounted on a press (fig. 4(a)). Pressure is applied until the tube conforms to the die cavity contour (figs. 4(b) and 4(c)). The forming is dependent on the material forming characteristics, and in the case of alloy steels, two or more forming steps and intermediate annealing treatments are necessary to completely form the tube satisfactorily without creating longitudinal cracks along the leading and trailing edges. The wax inside the tube maintains a uniform blade-wall contour and gives closer control of the forming method. On blades that are internally clad with copper, a few thousandths inch of copper is removed from the inside of the leading and trailing edges to facilitate forming.

COOLANT-PASSAGE DESIGN AND FABRICATION

The necessity of increasing the heat-transfer area within the shell coolant passage made it necessary to investigate methods of adding additional internal metal areas. Fins with a large surface area with respect to occupied volume were desirable; however, insertion of fins, maintenance of uniform spacing, and attainment of fin-to-blade contact at all points made fabrication difficult. The use of tubes, although not so desirable in respect to the surface area - volume relation, were much easier to fabricate. Tubes can be inserted in the blade coolant passage and maximum wall contact can be easily achieved. This wall contact approaches line contact along the length of the tube and shell, and because of this close contact, the brazing metal fillets as shown in figure 5. This action assures good heat transfer through the braze joint, over-all tube-to-shell contact, and high shear strength between the tubes and the shell.

Brazing of fins or tubes involves selecting a brazing material to meet the following conditions:

(1) The brazing material must possess high wettability and flowability.

(2) The brazing alloy softening point must be well above the temperature at which the blade will operate.

(3) The brazing temperature must be below that which causes a deterioration of blade-metal properties.

(4) The brazed joint must have strength sufficient to withstand the vibratory stresses and the centrifugal shear stresses encountered at the temperatures of blade operation.

(5) The brazing material should alloy with both blade and tube to form a maximum heat-transfer bond.

These requirements were initially met by the use of Nicrobraze (formerly known as Wall-Colmonoy No. 6) for both the critical alloy blades and the steel alloy blades. Nicrobraze, however, gives a somewhat brittle joint if present in excess and therefore is notch sensitive and subject to fatigue cracking. A more ductile brazing material with possibly some sacrifice in mechanical properties would be advantageous. The use of pure copper as a brazing material for steel blades has certain advantages in that it fillets and alloys well with the steel; however, its strength properties are lower than those of Nicrobraze. Nevertheless, preliminary results from blade tests in turbojet engines indicate that copper brazing does result in sufficient strength for air-cooled-blade applications.

Fabrication of Tube-Filled Blades

The preparation of the blades and tubes for brazing comprises the following steps:

Internal blade preparation. - Precision-cast hollow shells and blades in most cases have a smooth internal surface, but occasionally there are small areas of metal projections due to investment cracking. These projections must be removed so that the tubes can be fitted to the passage. Formed steel shells do not require this operation. All shells are internally vapor blasted in order to obtain a clean surface for brazing. Steel shells should be acid pickled to remove scale before vapor blasting, whereas copper-clad shells should have a prior nitric-acid dip.

Tube preparation. - All tubes of either steel, stainless or copper-clad, are cut to the desired length, vapor blasted, washed, and dried before being inserted into the blade. The tubes must be straight and without end burrs.

Tube packing. - Optimum tube packing for high heat transfer and good brazing bond necessitates that each tube contact the internal blade wall along its length and that it also contact either the opposite blade wall or other adjacent tubes. The number of blade-tube and tube-tube contacts is important as these affect the transfer of heat from the blade surface to the internal blade coolant air. Optimum packing generally requires the use of varying tube sizes.

Suitable tube packs are illustrated in figure 5. The spaces between the tubes also have to be considered as possible air-coolant passages. Examples of various tube-packed blades and a finned blade are shown in figure 6.

Brazing. - Nicrobraze, copper-silver eutectic, and copper brazing powders were obtained with a fineness of 100 percent less than 300 mesh. The powders were mixed with a high melting liquid flux (1870° F) (Eutectic Flux No. 1605) or a borax-water flux in the ratio of three or four parts powder to one part flux. Water was added to give fluidity to the mixture so that good flow around the tubes was assured. It is important that the powder be well distributed inside the blade and around the tubes so as to obtain good filleting action. The mixture was then allowed to solidify within the blade for ease of handling. Brazing can also be accomplished without flux by the use of volatile plastic cement, such as Acryloid B-7. Copper wire of a specific diameter (dependent on amount of brazing metal required) can be substituted for the copper powder, and such wire can be laced through the passages where brazing is desired. This procedure gives excellent results.

Brazing is accomplished by heating the tube-packed blade containing the brazing compound to the brazing temperature in a controlled atmosphere furnace. The brazing temperature is dependent on the brazing alloy used. The following table lists the temperatures at which brazing is accomplished for the alloys used at present:

Material	Temperature ($^\circ$F)
Nicrobraze	2075
Copper	2025-2075
Copper-silver eutectic	1450-1475

Atmospheric control is highly important and in all cases a dry hydrogen atmosphere (dewpoint, -40° F) was used. This atmosphere is a necessity when using Nicrobraze in order to obtain good flow characteristics; atmospheres like ammonia and cracked gas can be used for the other brazing alloys. If the alloy to be brazed has sufficient chromium content to form chromium oxides readily on the brazing surface, the use of a dry atmosphere is a necessity.

The following specification for brazing on these blades gave good results for Nicrobraze:

(1) Braze in a dry hydrogen atmosphere (dewpoint, -40° F) at 2075° F, allow only enough time for flowing - no period soak at 2075° F. (Nicrobraze dissolves parent metal rapidly.)

(2) The blade should be positioned in the furnace with the concave side of the airfoil up and the extended tube pack and blade should be slanted down at about a 10° angle.

The tubes are extended beyond the blade opening as shown in figure 4(e) and the blade is slanted downward so that the excess brazing alloy will flow out of the blade cavity and not block the internal coolant passages. The tubes act as a capillary for the brazing alloy and draw the excess alloy from the internal passage.

Fabrication of Finned Blades

Steel fins (0.020 in. thick) were brazed into a blade shell by slitting opposite blade faces at 0.100-inch intervals and inserting the fins through these slots so that the fins projected above each of the blade surfaces by about 1/16 inch. Nicrobraze with flux was painted on the convex and concave blade surfaces between the fins and brazed under previously mentioned conditions. This brazing procedure was

repeated twice to fill out the outside blade contour completely. The
outside blade surface was then hand finished to the correct contour.
The completed blade is shown in figure 6 (third blade from left). This
fabrication procedure is costly and time consuming, but it gave a blade
in which the worth of fins could be evaluated. Other methods possibly
could be developed for production processes.

Fabrication of Simulated Finned Blade

The addition of fins in a blade, such as the finned blade in fig-
ure 6, provides an effective method of cooling the blade (reference 2),
but the fabrication of the blade is very difficult. The use of other
methods of increasing surface areas similar to that of adding fins is
therefore suggested. A possible method is the utilization of formed
sheet metal in the shape of a corrugation (fig. 7). A similar type of
blade where the corrugations were made by hand forming has been made
with little difficulty. The central portion of the blade is blocked off
for two reasons: (1) because the fin effectiveness decreases with
increased distance from the blade wall; and (2) on some blade designs a
certain amount of restriction is required to increase the coolant veloc-
ities and thereby promote increased heat-transfer rates.

Film-Cooled Blades

A number of film-cooled blades were fabricated. The slots used for
introducing the film of air were cut with a thin, small diameter
resinoid-type cut-off wheel on a surface-type grinder. The slot widths
varied, depending on the application, from 0.010 to 0.025 inch. The
leading-edge slots shown on the blade in figure 8(a) were cut at an
angle of 45° to the leading edge and were located so that adjacent slots
overlapped. This type of configuration creates high local stresses dur-
ing engine operation because of the notch effect of the slots and the
over-hanging metal between slots. This high-stress condition is allevi-
ated on the blade shown in figure 8(b), which has three rows of radial
slots at the leading edge. These slots lie on the same direction as the
radial forces and the excess stress concentration is therefore
minimized.

The trailing edges of the blades shown in figure 8 incorporated a
row of 0.040-inch-diameter holes placed 1/8 inch apart at the bottom of
a slanted groove that was ground along the trailing edge. Caps were
welded to the tips of the leading- and trailing-edge coolant passages.

A sketch and a photograph of another type of film-cooled blade
configuration are shown in figure 9. The trailing edge of this blade
contained a continuous slot with a support member at the midspan. The

slot was formed by grinding away a portion of the trailing edge on the
pressure surface of the blade and then cutting into the coolant passage
with a thin resinoid-type cut-off wheel. The tubes in the coolant pas-
sage of this blade were cut off 0.35 inch from the blade tip and the
blade was capped. The leading- and trailing-edge coolant passages were
also dammed at midspan by cutting slots at this position, inserting
dams, and welding them in place. Variations of this type of blade that
were also fabricated include (1) removal of the dams in the leading- and
trailing-edge passages, (2) utilization of a single row of slots
directly at the leading edge in place of the three slots shown, and
(3) placing the leading- and trailing-edge dams at the blade root
instead of at the midspan.

A blade that has a cap or shield at the leading edge to direct the
film-cooling-air flow along the blade surface is shown in figure 10.
The shield can be made of Inconel or stainless steel and is formed to
simulate the leading-edge contour of the blade. Slots or holes are
placed under the shield directly at the leading edge to feed the cool-
ing air from the coolant passage inside of the blade. The shield can
be attached by spot welding as shown in the figure or by plug brazing
or welding.

Convection-Cooled Blade

The convection-cooled blade shown in figure 11 was split so that
part of the cooling air discharged directly at the trailing edge. The
trailing edge was fabricated by splitting the entire trailing edge with
a 0.010-inch-wide resinoid-type wheel. Inconel shim inserts 0.012 inch
thick and 1/8 inch wide were placed in the split trailing edge at
5/8-inch intervals and spot welded in place. The purposes of the shims
were to support the two faces of the trailing edge and to control the
slot width. The trailing-edge cooling-air passage was capped at the
tip.

Conduction-Cooled Blades

Two blades that utilized copper to conduct heat away from the lead-
ing and trailing edges are shown in figure 12. The copper-clad blade
was made from copper-clad Inconel sheet stock that was rolled and seam
welded into a tube and formed as described previously. This blade
had a constant copper thickness of 0.020 inch, but the Inconel wall
was tapered from approximately 0.050 inch at the base to 0.020 inch at
the tip. This configuration is not considered optimum, however, parti-
cularly for copper-clad steel. It would be advantageous to have a some-
what higher taper ratio on the steel supporting shell and, in addition,
the copper could also be tapered from root to tip. Because the primary

purpose of the copper is to conduct heat away from the leading and trailing edges, and the midchord region of the blade has essentially a constant temperature, the copper in the midchord region acts mainly as dead weight and most of it could be removed by a broaching operation either before or after the blade was formed. The blades shown on figure 12 also contained copper tubes. Since no increase in blade effectiveness has been observed when changing from steel to copper tubes (references 4 and 6), steel tubes could be used in the blades to decrease the shell stresses. A brazing metal that has been found successful for attaching copper to copper or copper to steel is a eutectic of copper and silver (28.5-percent copper; 71.5-percent silver).

The copper-fin insert blade, shown on figure 12, can be fabricated two different ways, depending on the type of tube inserted in the passage. The blade shown had copper tubes and all the brazing was done in one operation. If the tubes had been steel, two brazing operations would have been necessary. For a blade containing all copper tubes, the trailing edge of the blade shell was split with a 0.025-inch-wide resinoid-type wheel, which left an opening of approximately 0.030 inch. Copper fins 0.030 inch thick were first attached to copper tubes by a 1600° F alloy; the melting temperature was higher than the 1450° to 1475° F brazing temperature of the copper-silver eutectic used for the final operation of brazing the copper tubes and fins to the steel or cobalt-base alloy shell. The tubes and fins were then inserted into the blade and brazed in the usual fashion.

When steel tubes were inserted into the shell, the tubes, with the exception of the two end copper tubes that are attached to the copper fins, were first packed into the blade shell. Ceramic tubing, which repels brazing materials, of the same diameter as the copper tubes was inserted in the place of the two copper tubes. The steel tubes were then either Nicrobrazed or copper brazed to the shell, after which the ceramic tubes were removed from the blade. The trailing edge was then split as before and the copper tubes with attached fins were inserted. The copper tubes and fins were then brazed with a lower melting copper-silver eutectic.

FINAL BLADE-FABRICATION OPERATIONS

The final blade-fabrication operations include attachment of the blade shell to the base, blade heat treatment, base-serration grinding, and cutting the blade to length. These operations are explained in the following paragraphs.

Attachment of Blade Shell to Base

Cobalt-base alloy shells were welded to a similar alloy base by heliarc-type welding with a rod of S-816 alloy. For the steel blades, heliarc welding with a preheat and using an aluminum-dip-coated SAE 4130 steel rod gave excellent results with good penetration and high tensile strength. The thin aluminum coating on the rod was used to minimize boiling in the weld. Penetration and internal oxidation were controlled by the use of a helium atmosphere flowing through the internal coolant passages.

For cobalt-base alloy blades, the shell and base were ground flat and parallel. The shell was chamfered at the base juncture to obtain better weld penetration. The assembly was tack welded in a jig and then fillet welded. For steel blades, a butt-welding technique is considered superior to fillet welding because better penetration is obtained. In the butt-welding method, a lip having the same profile as the blade shell is cast onto the base. The blade shell is then chamfered and butt welded onto the lip. This type of weld gave excellent weld penetration, but hand grinding was required to restore the proper blade contour in the welded region. Tensile tests of such a blade resulted in fracture in the blade shell and not in the weld.

Welding of the shell to the blade base can be done either before or after tubes or fins are inserted into the shell. There are certain advantages and disadvantages to either procedure. If the shell is welded to the base before the tubes are installed, the weld metal that penetrates into the coolant passage has to be removed in order to permit the tubes to extend into the base. Extension of the tubes provides a stronger tube support and decreases the shell stresses. Removing this metal from the inside of the blade is a tedious process. If the tubes are inserted into the shell first and fitted into the base, a very good tube pack can be obtained that is in close contact with the shell and base at all locations, and when the shell is welded to the base the weld metal that penetrates to the coolant passage also firmly anchors the tubes in place. The only disadvantage in this procedure is that the weld metal partly blocks the cooling-air passage between adjacent tubes. Nevertheless, the second method is believed preferable. In all cases the tubes are brazed to the shell after welding the shell to the base.

Another shell attachment method that shows considerable promise is for a formed blade shell to extend through the blade base. The shell is then furnace brazed into the base. Such a brazing operation requires a 0.003- to 0.005-inch fit between the shell and the base cavity. Because the shell is tapered, the strength of the attachment is increased by mechanical locking. A fillet is added at the juncture of the blade and the base by torch brazing to relieve stress concentrations in that region. The base and the blade are generally furnace brazed with Nicrobraze at the same time that the internal tubes are brazed into the shell.

In addition to the high strength obtained by this attachment method, the coolant passage is uniform through the shell and blade base with no air restrictions caused by shell attachment. This method simplifies fabrication and also provides increased cooling effectiveness by providing a better distribution of the cooling air.

All welding procedures involve stress-relieving treatments and the welds should be radiographed. For steel welds, the weld can also be magnafluxed. Gross defects are cause for rejection; however, many weld defects can be ground out and rewelded.

Blade Heat Treatment

The precision cast cobalt-base alloy blades were given only a stress-relieving treatment for the base attaching welds. Steel blades, however, require special heat treatment for increased creep and rupture strengths. Data have indicated that a normalizing and tempering treatment increases rupture and creep properties, and that a high austenizing temperature with controlled isothermal quenching is even better (reference 7). Test data in support of reference 7 have been determined and blades with this treatment have shown little tendency towards creep and have markedly improved life in engine tests at the Lewis laboratory. The following table gives heat treatments that have been used for various steel blades:

Steel type	Solution temperature (15 min) (°F)	Quench	Draw		Isothermal transformation (15 min) (°F)
			Temperature (°F)	Time (hr)	
SAE 4130	2000 or 2075	Air	1200	1/2	- - -
SAE 4130	2000 or 2050	---	- - -	---	1000
17-22A[S]	2000 or 2075	---	- - -	---	1200
17-22A[S]	1750	Air	1200	6	- - -

Steel blades can be heat treated at any time after brazing; however, it may be advantageous with regard to production to heat-treat directly after brazing for the brazing temperature is often the initial temperature in the heat-treating cycle. Salt-bath treatments after brazing introduce the problem of removing the heat-treating salts from the small coolant passages in the blade. A controlled atmosphere furnace is therefore more applicable for the initial austenizing treatment. A lower temperature salt bath (1000° F) can be used directly on isothermal quenching from the brazing operation, and this salt is highly water soluble.

Finish Operations

Blade-base serrations are cut after heat treatment. The usual pro-
cedure is to grind the serrations using a crush-type grinding wheel;
however, the serrations can be cut by either milling or broaching for
either cobalt-base or steel-alloy blades.

After the base serrations are made the blade is ready to be cut to
final length and excess metal on the ends of the base can be removed.
The blades are usually ground to length; however, if a large amount of
material is to be removed, a cut-off wheel can be used before grinding.

SUMMARIZATION
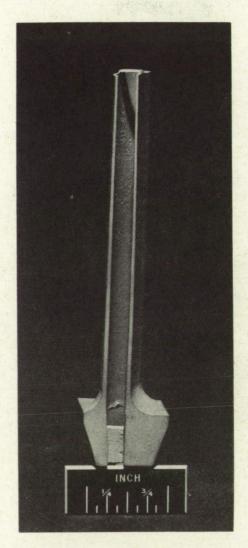
Fabrication procedures for a wide variety of cooled turbine-blade
configurations can be summarized as follows:

1. Cooled-blade shells can be fabricated successfully by either
casting or forming processes. The shells can be cast integrally with
the blade base, or shells cast or formed separate from the base can be
attached by either welding or brazing techniques.

2. Internal heat-transfer surface area can be provided by the addi-
tion of tubes, fins, or corrugations in the blade coolant passage by
the use of correct brazing techniques.

3. Blades have been fabricated with special means of cooling the
leading and trailing edges, including several methods of film cooling,
two methods of conduction cooling, and a special means of convection
cooling the trailing edge.

4. The cooled-blade configurations that could probably be best
fabricated by production processes would be formed blades containing
tubes or corrugations brazed in the coolant passages with possibly the
use of internal copper cladding to conduct heat away from the leading
and trailing edges.

5. Attachment of a formed blade shell to the blade base can be
best accomplished by inserting the tapered shell through the base cavity
and then furnace brazing it to the base.

6. The proper heat treatment of steel blades increased the life of
such blades in actual engine operation by a large factor.

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    National Advisory Committee for Aeronautics,
        Cleveland, Ohio.

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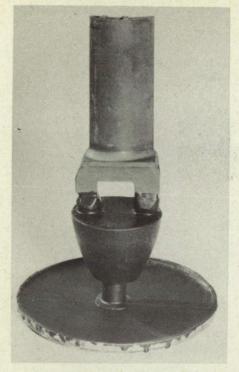
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     Aug. 18, 1950. (Contract W-33-038-ac-21094.)

Figure 1. - Cross section of integrally cast blade and base.
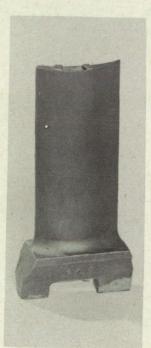
(a) Wax pattern with one type of pouring
    basin and gates attached.

(b) Investment flask.

(c) Rough casting.

(d) Finished casting.

Figure 2. - Steps in precision casting of hollow blade.
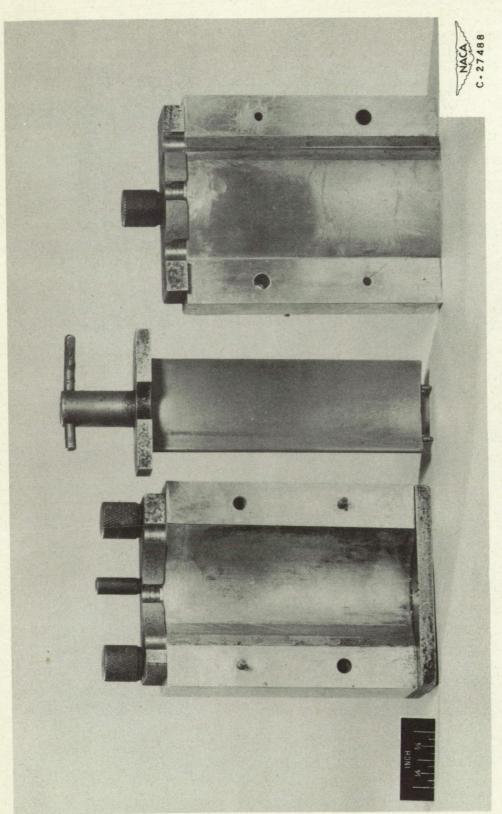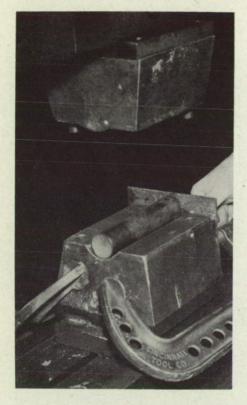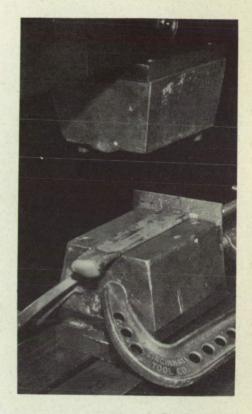
Figure 3. - Machined die for wax patterns.
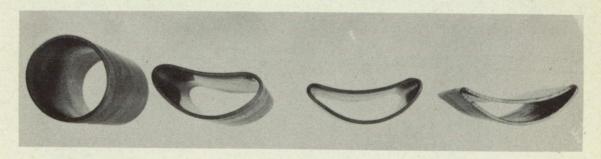
(a) Wax-filled tube in die.

(b) First forming operation.

(c) Steps in the forming operation.
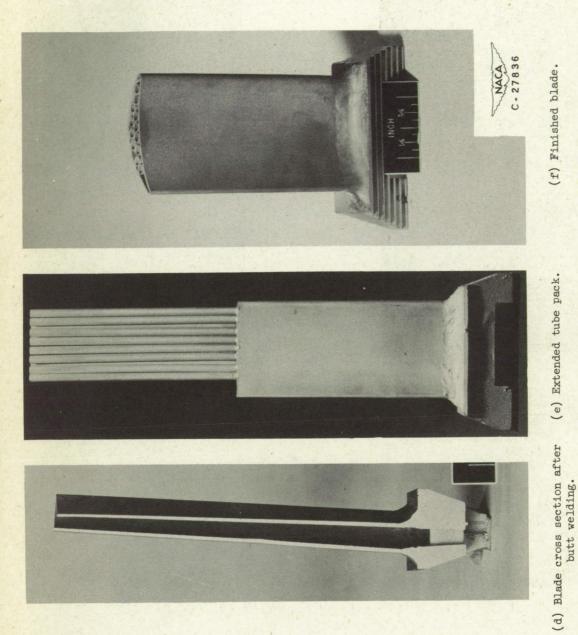
Figure 4. - Steps in formed blade fabrication.

(d) Blade cross section after   (e) Extended tube pack.   (f) Finished blade.
    butt welding.

Figure 4. - Concluded. Steps in formed blade fabrication.
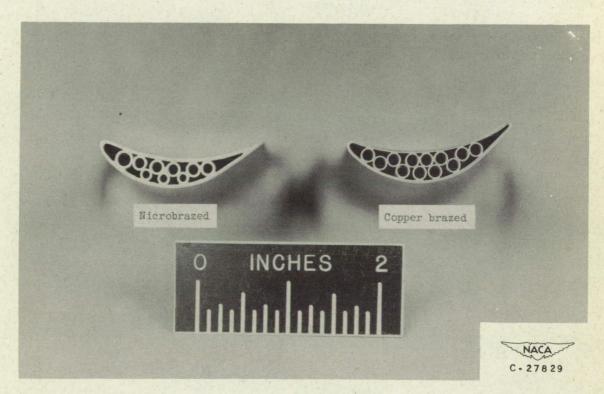
Figure 5. - Examples of suitable tube packs and tube brazing.
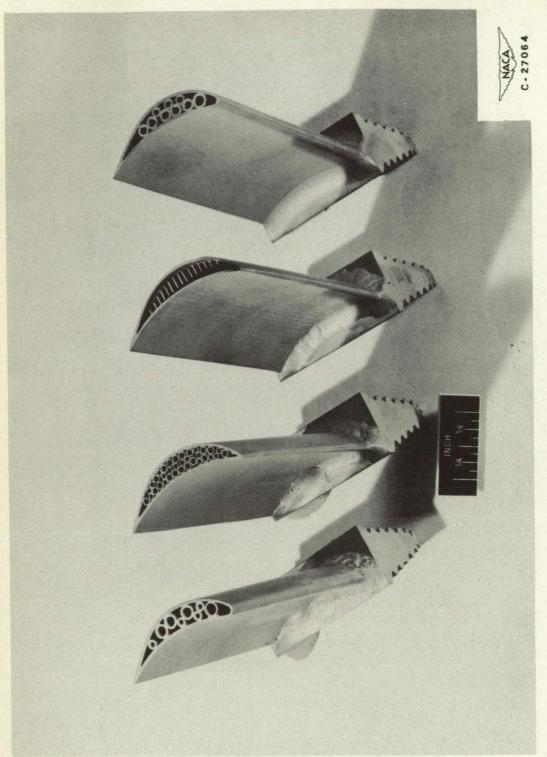
Figure 6. - Examples of tube filled and finned turbine blades.
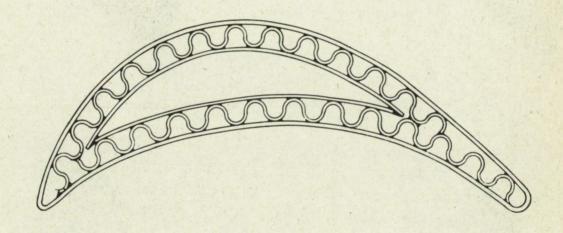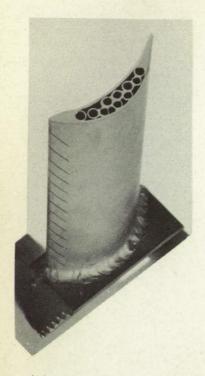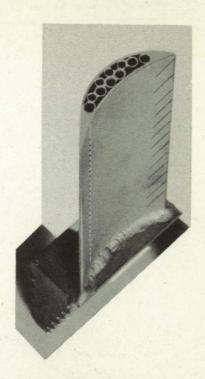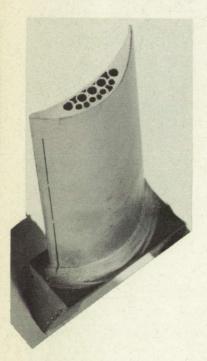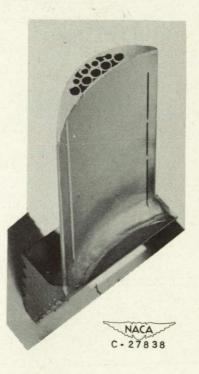
Figure 7. - Simulated finned blade.

(a) Herringbone slots in leading edge and 0.040-inch-diameter holes in trailing edge.

(b) Three rows of radial slots in leading edge and 0.040-inch-diameter holes in trailing edge.

Figure 8. - Leading- and trailing-edge views of film-cooled blades.
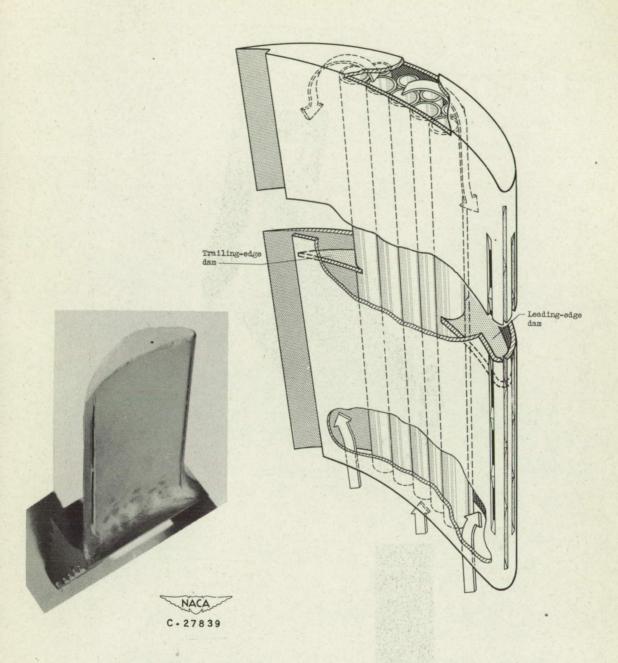
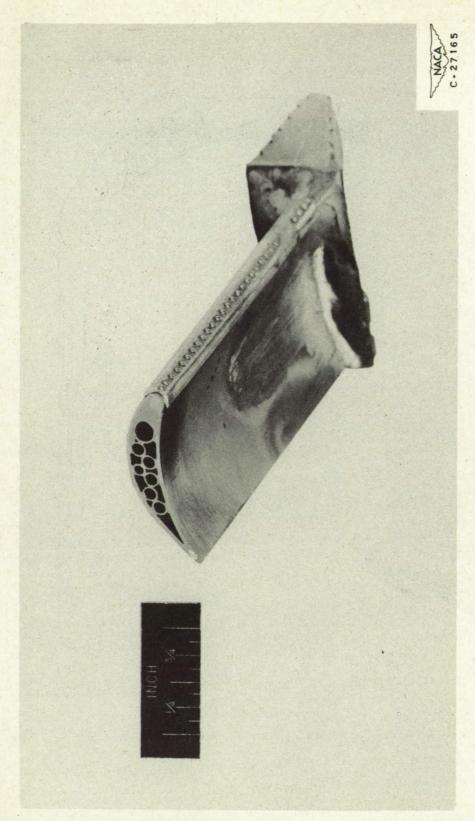Figure 9. - Film-cooled blade utilizing double-flow coolant path.

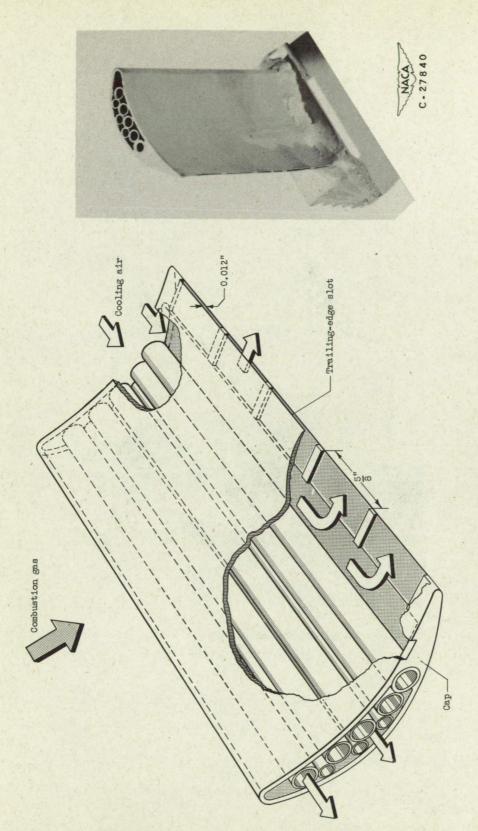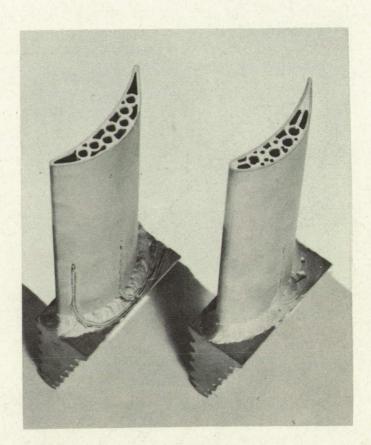Figure 10. - Film-cooled leading-edge blade incorporating a cap or "false nose."

Figure 11. - Blade utilizing convection cooling at trailing edge.

Figure 12. - Conduction-cooled blades using copper cladding and copper fin inserts.